Paper No. 57

MICROMETEOROID IMPACT SIMULATION SYSTEM

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REFERENCE: Robert A. Golub and John R. Davidson, "Micrometeoroid Impact Simulation System," ASTM/IES/AIAA Space Simulation Conference, 14-16 September 1970.

ABSTRACT: This paper describes a Micrometeoroid Impact Simulation System (MIMS) at NASA Langley Research Center and outlines current research efforts. The MIMS electrostatically accelerates electrically charged, micrometer-size particles to velocities in excess of 30 km/s. Particles can be accelerated one at a time or at various rates to above 10/s. The major components of the MIMS are a microparticle charger-injector, a horizontal 4-million-volt Van de Graaff accelerator, an assemblage of particle detectors, a particle deflection system, a data system, and a series of target chambers. The data system is a computer-controlled, real-time system which records information to determine the velocity, mass, and diameter of each particle which enters the target area. The system also controls and selects particles, and rejects particles which do not have the desired velocities. The system is used to study damage to sensitive surfaces, develop micrometeoroid detectors, and obtain data about meteoroid entry physics.

KEY WORDS: micrometeoroid, hypervelocity, particle detectors, impact damage

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The existence of meteoroids in space presents a hazard to vehicles and satellites outside of the earth's atmosphere. The particle sizes vary greatly, with the smallest being about 1μm in diameter. Their velocities vary from about 11 to 72 km/s.

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The small particles, called micrometeoroids, can damage the surfaces of space telescopes, external windows on spacecraft, lenses, protective coatings, and exposed instrumentation. The damage is the result of both a high particle flux and long exposure time which causes a gradual deterioration of the surface efficiency. To establish a damage criteria and degradation rates, the cumulative effect of micrometeoroid impacts must be measured.

A Micrometeoroid Impact Simulator (MIMS) was built to measure these phenomena. The major components of the simulator system are a microparticle charger-injector, a horizontal 4-million-volt Van de Graaff accelerator (VDG), an assemblage of particle detectors, a particle deflection system, a unique data acquisition system, and a series of target chambers. The simulator has accelerated micrometer-size, spherical particles to velocities in excess of 34 km/s. It can provide particles at rates in excess of 10/s.

The purpose of this paper is, first, to describe the MIMS and, second, to outline the current experimental studies.

MIMS THEORY OF OPERATION

The basic principle under which the system functions is the conservation of energy. It states that a particle with charge, q, put in a potential field V, will change kinetic energy by an amount equal to the product of V and q. Mathematically,

$$\frac{1}{2} mv^2 = Vq$$

where m is the mass of the particle and v is the velocity of the particle. Solving the equation for the velocity:

$$v = \sqrt{2\ Vq/m}$$

The resultant velocity, then, is a function of the potential field V, the charge on the particle q, and the particle mass m. From theory and geometry q varies as $\sqrt{V/d}$ and since the machine voltage is usually fixed and the charger-injector maintains a relatively constant charging efficiency, the velocity will vary with particle size; the smallest particles will have the highest velocities. Figure 1 shows the variation of the velocity with particle size. With the simulator system at 4-MV, 0.1 μm diameter particles are accelerated to velocities about 35 km/s and 10μm diameter particles to velocities of about 4 km/s.

A diagram of the system is shown in Figure 2. The vacuum environment through which the particles travel is maintained by the VDG vacuum system and the vacuum systems of the adjoining target chambers. A particle is accelerated as follows: The particles are initially at rest in a cavity in the charger-injector. A particle is given a charge and then injected into the VDG along the accelerating axis. Once in the field of the VDG, the particle is focused and accelerated through the full potential of the machine. After it leaves the VDG, the particle is traveling at a constant velocity. It then traverses several particle detectors where its charge-induced voltage, time of flight, and the potential by which it was accelerated are measured by the data system. If the particle is within preset time-of-flight limits, it is counted, has its measured parameters recorded, and is allowed to pass through the deflection system without being deflected. On the other hand, if the particle does not have the proper velocity it is considered unacceptable, is not counted, does not have its parameters recorded, and the deflection system deflects it into a deflection aperture plate where it is stopped before it can enter the target chamber. The data system records the parameters for those particles which it has allowed to pass into the target area.

The particle beam size is controlled with the VDG focusing system. A focused particle beam would contain about 90 percent of the particles within a 1-mm-diameter area. A defocused beam, which is useful in some experiments, can be as large as about 6 mm in diameter.

The particles normally used are carbonyl-iron. Their density is 7.86×10^3 kg/m^3 and their diameters range from about 0.1 to 10μm. Particles can be injected either by manual operation or by automatic operation at rates of 0.5, 1, 2, 5, or over 10 per second.

PARTICLE CHARGER-INJECTOR

The charger-injector is shown in Figure 3. Details of operation are available in reference 1. The methods for charging and injecting particles will be described briefly. The particles are initially at rest in the particle cavity. The charging electrode-particle cavity assembly and the plate are maintained at a potential of about 12 to 14 kV. A negative pulse is then applied to the plate which causes the topmost layer of particles to achieve erratic motion. This motion is similar to that of particles in a gas. Some of these particles will effuse through the cavity exit into the forward charging chamber. Of the particles which pass into the forward charging chamber which are still in motion, some will strike the electrode and gain a very high charge. When one of these highly charged particles passes through the collimating apertures, it is focused and accelerated by the VDG.

A charging electrode is shown in the figure inset. It is basically a tapered shaft with a small ball at the end. The shaft length is about 2.5 mm and the diameter of the ball is about 30μm. The electrode is usually tungsten. For particle rates of about 10 per second, the average operating lifetime of a good charging electrode is about 40 to 80 hours. The application of a 12 to 14 kV potential on the electrode results in a charge transfer to a particle amounting to about 12 to 14 percent of the theoretical maximum charge that the particle can hold. If the electrodes are operated at higher potentials, the charging efficiency does not increase appreciably but the electrode lifetime is shortened considerably.

ACCELERATOR

The 4-MV Van de Graaff Accelerator (Model KN-4000) is operated in a positive mode. The high potential is attained by transferring charge from a power supply located at the base of the machine (via a specially woven, continuous belt) to the high voltage dome. Figure 4 is a photograph of the VDG with the outer tank and the dome removed to show the high voltage end of the column where the terminal electronics of the machine are mounted. The primary components of the column are porcelain insulating supports, a series of rings coupled by resistors, the accelerating tube, and a drive motor and alternator pully which hold the belt. The alternator also supplies power for use inside the high-voltage dome. The particle charger-injector and its electronics can be seen in the end of the column. The column is cantilevered from a heavy base plate which is anchored to the floor. In order to operate the accelerator, the tank must enclose the column and be sealed to the base plate. The tank is pressurized to about 550 kN/m^2 (80 psig) with sulfur hexafluoride gas. The SF_6 is an excellent insulating gas and allows operation at 4 to 4.5 MV with almost no machine sparking. The accelerator operates stably if it has been properly prepared for running. At 4 MV the terminal voltage variation can be held below ±10 kV with some effort.

DETECTORS

The velocity, charge, and position detectors are identical electrically and differ only in the configuration of the active elements. Figure 5 shows a diagram of a typical detector. The detector is a coaxial capacitive pickup consisting of an inner active element through which the particles pass, a bootstrap shield, and a vacuum-enclosure support outer tube. The detector active element behaves like a capacitor and senses a passing charged particle. The governing equation is:

$$q = CV_o$$

where q is the particle charge, C the detector capacitance, and V_o the induced voltage. A typical detector waveform showing the voltage V_o as a function of time for a passing charge particle is shown in Figure 5. The bootstrap shield is operated by negative feedback from the detector amplifier and drives the electrical capacitance of the assembly to a lower effective value. This bootstrap shield action increases the sensitivity of the detectors. These detectors can reliably sense charges as small as about 1 fC.

TARGET AREA

The arrangement of the target chambers is shown in Figure 6. The target chambers are deliberately arranged in a "piggyback" style. The arrangement facilitates quick experimental changeovers by minimizing the alinement problems. Each chamber is independent of the others because each has its own vacuum system and can be closed off from the others. The first chamber, which is called the single-impact chamber, contains a movable, remotely controlled, target positioner. The positioner can move the target across the beam horizontally and vertically to about 5 cm from the center line. The positioner also contains a gimbal system and can allow pitch and yaw motions of the target to $\pm 45^\circ$. The chamber has two 12.5-cm glass ports so that the target can be seen from the front at angles of 45°.

The second chamber is used for mirror surface tests and impact flash experiments. It has two chamber sections on a common axis. The first section contains two sets of parallel plates which are alined along the particle beam axis; one set is perpendicular to the other. The plates deflect the particle beam when a modulated high voltage is applied to each set of plates. In this way, the surface of a mirror can be scanned with the beam. The impact flash section has four equally spaced, 5-cm front viewing ports and one 5-cm rear viewing port. All of the 5-cm ports have retainers for mounting filters and photomultiplier tubes.

The third chamber is a specially designed, two-stage, differentially pumped system used for luminosity and drag experiments. The chamber test section, which can be at pressures as high as 300 N/m^2, can be coupled to the other vacuum systems which are at about 10^{-4} N/m^2 (10^{-6} torr). The test section is about 15 cm in diameter and over 1 m in length. It has fifteen 5-cm diameter ports along its axis to view particle luminosity.

DATA SYSTEM

The data system, in addition to recording data, also controls the particle beam. The computer-controlled interface coupled to the multielement detector system selects particles with desired velocities and controls the number of particles which strike the target. The data system can accept particles with velocities from less than 1 km/s to velocities greater than 40 km/s. It measures the charge-induced voltage of the particle, time of flight of the particle, and the potential of the VDG for each particle within preset velocity limits. From these three parameters the velocity, mass, and diameter of a particle can be calculated.

Equipment

The MIMS control room is shown in Figure 7. The three instrument racks at the left contain the controls and monitoring equipment for the VDG and the particle charger-injector. The other components are parts of the data system; they are the computer, the interface rack, the magnetic tape unit, the keyboard/printer-punch/reader, and the card reader.

The computer has a 16-bit word length and multiple hardware registers. It contains 16,000 words of core memory to hold the MIMS control program. The control program is a real-time program and uses the interrupt features of the computer for selection of functions. The operator controls program functions with the data switches and the interrupt switch on the computer control console.

The magnetic tape unit, the card reader, and the keyboard/printer-punch/reader are standard computer peripheral devices. They are used to store data, to modify the program, and for operator control of the data system.

The interface rack is a specially designed unit. It contains:

1. A dual counter scaler unit for counting particles.
2. A time interval counter for measuring particle time of flight.
3. An analog-to-digital converter (ADC) for measuring charge-induced voltage and VDG potential.
4. The control unit for the deflection system.
5. Two logic chassis which handle the real-time signals for the system.

Figure 8 shows the multielement detection system and the deflection system. Detectors V1, V2, and V3 are particle velocity sensors. Detector CH-1 is used to sense the particle charge-induced voltage. Detectors P1 and P2 are position detectors and are used only to aline the detector system to the particle beam. The deflection plates, the deflection aperture plate, and the deflection system power supply can be seen between detectors V3 and P2.

Method of Operation

Basically, the system works as follows (see Fig. 9): A particle passes through detector V1 and starts the time interval counter and a 1-MHz clock counter. If the particle gets to detector V2 (40 cm downstream from detector V1) it stops the 1 MHz clock counter; the clock counter value is stored in a storage register, and the clock counter is reversed so that it counts down to zero. Meanwhile the stored count (from the 1-MHz clock counter) is compared to two preset time-of-flight limits which form a "window." If the particle is within the limits then it is tentatively accepted; otherwise the system is reset and waits for another particle. When the 1-MHz clock counter reaches zero, the particle should be within the active element of detector CH-1. The analog-to-digital converter is given a convert pulse which tells it to convert the charge-induced voltage of the particle. The stored count (time value) is now loaded back into the 1-MHz clock counter and the clock counter is started to count down a second time. If the particle gets to detector V3, which is 1 m from V1, then the time interval counter is stopped and the particle is counted as an acceptable particle. Now the charge-induced voltage and velocity of the particle are read into the computer. The particle should reach the entrance to the deflection plates (40 cm downstream from detector CH-1) when the 1-MHz clock counter reaches zero for the second time. This clock counter triggers a pulse to remove the 10 kV from the deflection plates for a short period of time to allow the particle to continue in a straight line path. The particle is then free to enter into the first of the target chambers. If, for some reason, the particle had been unacceptable, that is, had either an unacceptable velocity or had struck one of the detectors and failed to get through the detection system in the proper timing sequence, the 10-kV potential would not have been removed from the deflection plates and the unwanted particle would have been deflected into the downstream deflection aperture plate. During the period in which a particle was between detector V3 and the deflection plates, the ADC was given a signal to convert a value from the VDG for the accelerating potential and subsequently store it in the computer. When sufficient particles have been accepted, the data stored in the computer memory are automatically transferred to magnetic tape for later analysis. Each time a particle is counted by the system it is compared to a preset maximum allowed particle count which, when reached, automatically terminates data system activity.

Data Output

Data can be output during real-time operation to a printer and stored on magnetic tape. In Figure 10 is shown a printer listing from a typical experimental run. At the top is the computer program initialization which tells the operator about his system options. In this case Mode A has been selected. This is a real-time mode where the accumulated data will be automatically transferred to the magnetic tape for storage. The alphabetic information starting with "PROJECT NUMBER" and ending with "USE DS, AND INTERRUPT TO GO" is typed out automatically in sequence. At the end of each line the operator supplies the numeric information. When the last numeric digit is typed, the project number, specimen number, and file reference number are automatically transferred onto the magnetic tape for identification. After the run has begun, the operator may print particle data on the printer at any time. If the operator interrupts the computer, the parameters will be printed for the next particle the system accepts after the interrupt was performed. When the operator terminates a run or (automatically) when the maximum allowed particle count limit is reached, the data system will stop operation, type out "END OF RUN," and await further instructions from the operator.

Mode B is like Mode A except that the tape identification is not generated (PROJECT NUMBER through FILE REFERENCE NUMBER) and the data are not stored on magnetic tape.

Mode C prints out any data which have been stored on the magnetic tape for checking or analysis.

Mode D is a test mode which gives a quick and simple system test of the velocity limits, the ADC conversions, and the time-of-flight measurement.

The data collected on magnetic tape are analyzed on a digital computer at Langley Research Center. Programs exist which read the data from the tapes and calculate parameters such as particle charge, velocity, mass, radius, momentum, and kinetic energy. Typical outputs of data are shown in Figure 11. Figure 11(a) shows a data display for the relative frequency of occurrence (for particle velocity). Figure 11(b) shows the results of a more extensive analysis and shows the log of kinetic energy versus relative frequency of occurrence.

Listed in Table 1 are some data which illustrate the system capabilities. Time-of-flight limits were selected in deliberate groups. The system was required to allow only one particle to be accepted during each run. The data illustrate that the data system can control the particle velocity by using the preset velocity limits. Particles in the 10-km/s range are available at rates of several particles per minute. For particles with velocities in excess of 30 km/s, the rate is about one particle in about 15 minutes when the system is set to shoot particles of 10/s. The calculated radii and masses for each particle are listed. The velocities and radii listed show that the smaller particles are the fastest, as predicted by theory.

EXAMPLES OF MICROMETEOROID EXPERIMENTS

The experimental programs presently underway are concerned with damage to sensitive surfaces, micrometeoroid detectors, and meteoroid entry physics.

Mirror surfaces, such as those to be used in the reflecting telescopes proposed for the manned space station, will be struck by micrometeoroids. A study is underway at the MIMS facility to show how the specular and diffuse reflectance change when such surfaces are bombarded with microparticles. Coated aluminum mirror surfaces have been bombarded with up to 10^9 particles/m^2. The narrow angle specular reflectance changes are being measured.

The simulator is being used to test and evaluate thin-film, capacitor-type micrometeoroid detectors. These detectors will be flown on the Meteoroid Technology Satellite. The satellite has three objectives: to measure meteoroid penetration rates in bumper protected structures (the rates will be compared with data from previous satellites which had unprotected sensors); to measure the velocities of meteoroids which penetrate stainless-steel sheets 13μm thick; and to measure the impact flux of small mass meteoroids in near-earth space. The thin-film capacitor detectors (about 1 or 2μm) are part of the velocity measuring sensors, and also detect the small-mass meteoroids. The characteristics of the detector discharge and the meteoroid parameters which trigger the discharge are not fully understood. Particle characteristics are being correlated with discharge signal characteristics to establish specifications for flight hardware. Also, because the velocity measuring device uses a thin-film capacitor bumper, the effect of the bumper on possible particle breakup is being studied. Thin-film capacitor detectors of 0.2 and 0.4μm thickness are also being studied.

When micrometeoroids hit a surface a flash of light is given off; this could be detrimental to space experiments which use photosensitive materials. The intensity-history of the flash and the spectral characteristics are being measured. If these are known, it may be possible to discriminate against them. Various kinds of targets, both hard and soft, are being tested. Preliminary measurements indicate that the flash from soft targets is somewhat different from the flash from hard targets. Other experiments suggest that the impact flash characteristics can be correlated with projectile characteristics, consequently the flash may be used both to detect micrometeoroid impacts and to identify the velocity and mass of the impacting particle; correlations of this type are being studied.

The MIMS solid-state detector studies are an effort to develop a reliable, long-life micrometeoroid impact detector for particles with masses as low as approximately 10^{-16} kg. Presently, no detector exists for these particles. Solid-state detectors are used by nuclear physicists to analyze particulate radiation. Three types of these solid-state detectors being studied for micrometeoroid measurements are:

1. Lithium-drifted silicon detectors
2. Silicon heavy-ion detectors
3. Silicon surface-barrier detectors

To date, two of the lithium-drifted silicon detectors have been tested with encouraging results. Every microparticle which struck the first detector generated a signal. The second detector was bombarded by over 700,000 particles intermittently during a several-day period and was still giving out signals when the run was terminated. Two surface-barrier-type detectors were tested but both of these failed after only a few impacts.

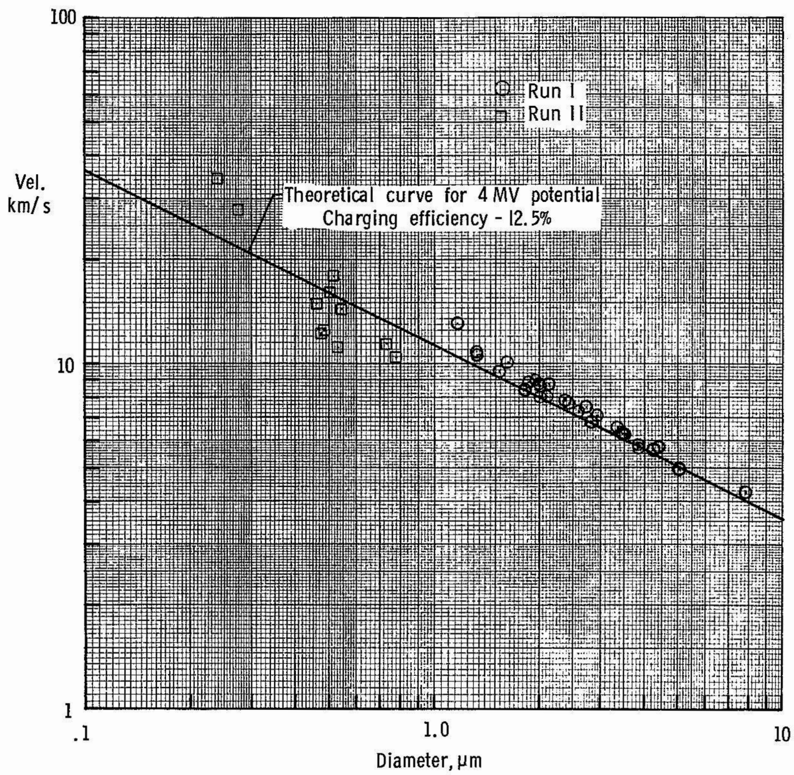
For the luminosity and drag experiments, a program is being developed at the MIMS facility on the laboratory simulation of meteor phenomena and associated atomic collision processes. A differentially pumped vacuum chamber is being used to provide a rarefied atmosphere. The particle is shot into the gas and, depending upon conditions, may cause a streak of light or be decelerated. Both the light trail and the particle deceleration will be measured. It is hoped that the results will supply data about the luminous efficiencies of meteors and help calibrate meteor photographs and radar observations.

CONCLUDING REMARKS

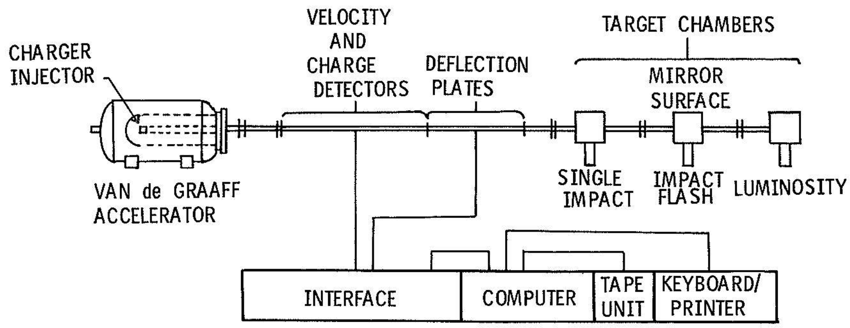
The Micrometeoroid Impact Simulator is one of the few apparatus which can accelerate particles of known mass to meteoric speeds (above 11 km/s). With the data acquisition system now in operation, the velocities of the impacting particles can be controlled and all particle parameters recorded for future automatic data analysis. The automatic features of the system permit the effect of thousands of particles on sensitive surfaces to be measured and analyzed. The simulator is being used to study the effect of micrometeoroids' impacts upon sensitive surfaces, and to develop new micrometeoroid sensors for flight experiments.

TABLE 1--Demonstration of Particle Velocity Control

Particle No.	Time of Flight Limit (μs) Slow	Fast	Particle Time of Flight (μs)	Velocity (km/s)	Diameter (μm)	Mass (kg × 10^{-16})
1	100	5	95.14	10.51	0.774	10.92
2	100	5	81.57	12.25	.476	4.44
3	100	5	80.71	12.39	.472	4.34
4	100	5	86.48	11.56	.714	15.01
5	100	5	88.35	11.31	.526	6.04
6	75	5	66.46	15.04	.456	3.91
7	75	5	54.13	18.47	.510	5.51
8	75	5	61.49	16.26	.496	5.03
9	75	5	68.80	14.53	.534	6.83
10	40	5	35.54	28.14	.272	.836
11	30	5	28.92	34.58	.236	.551



'igure 1. - Variation of microparticle velocity with diameter for 4-million-volt potential.



DATA ACQUISITION SYSTEM PERFORMANCE CHARACTERISTICS

CARBONYL IRON PARTICLES; DENSITY 7.86×10^3 kg/m^3

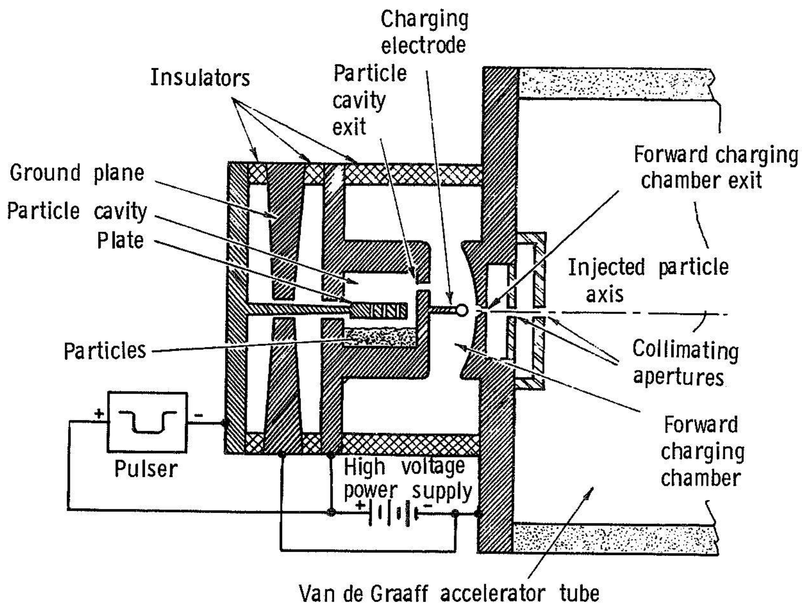
PARTICLE DIAMETER RANGE; 1 to 10 µm

PARTICLE RATES TO GREATER THAN 10/s

PARTICLE VELOCITY RANGE; $1 > v > 35$ km/s

MEASURES AND RECORDS PARTICLE PARAMETERS

Figure 2. —Micrometeoroid Impact Simulator System.



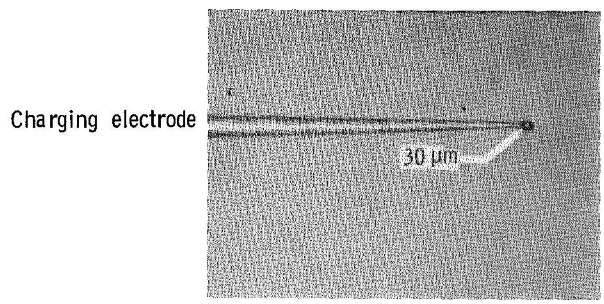


Figure 3. —Microparticle charger-injector.

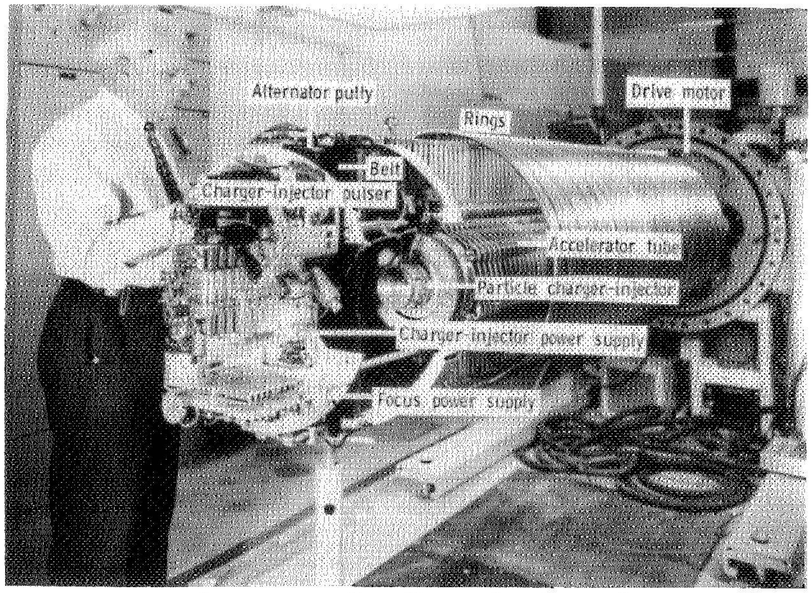
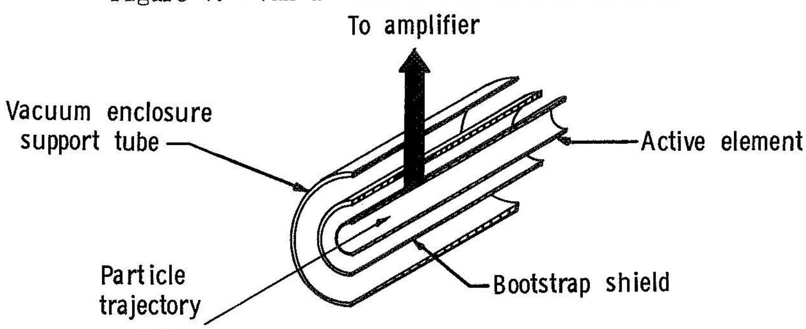
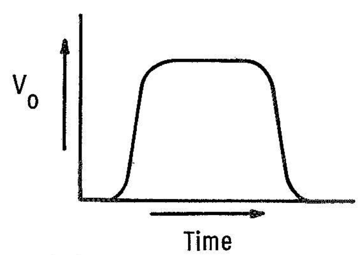


Figure 4. —Van de Graaff accelerator column.



(a) Section showing the detector elements.



(b) Typical detector waveform.

Figure 5. —Detector schematic and waveform.

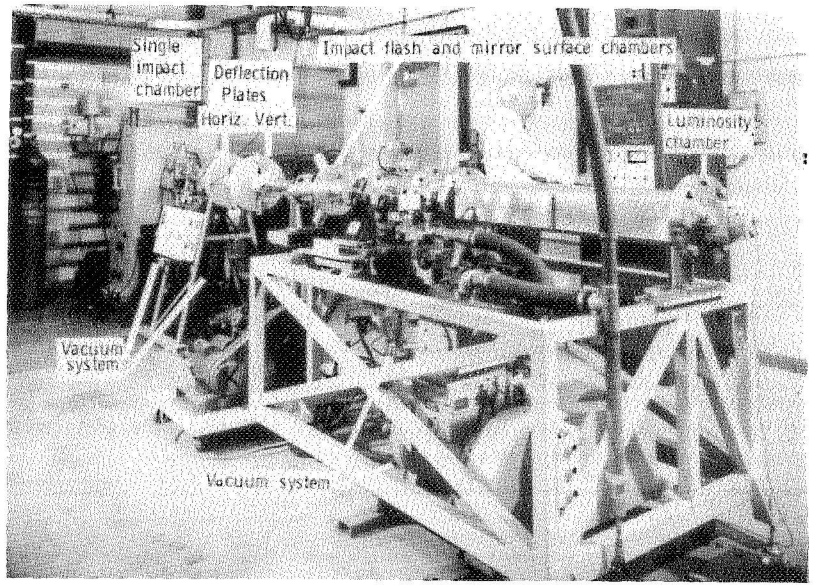


Figure 6. —Target chambers.

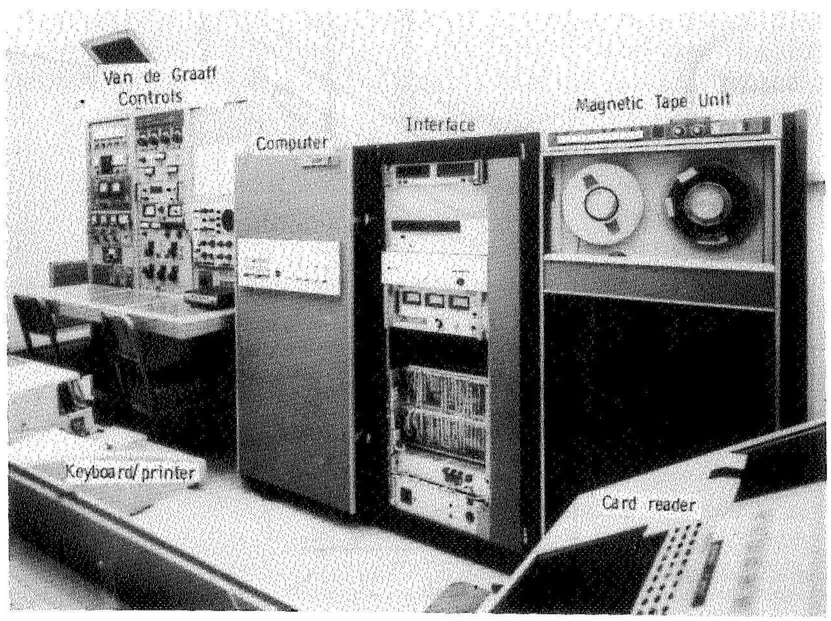


Figure 7. —MIMS control room.

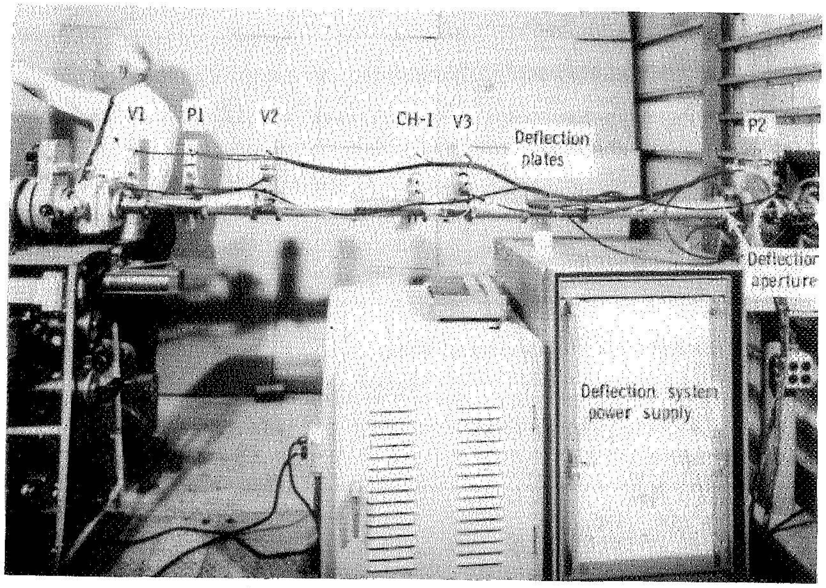


Figure 8. —Detector and deflection systems.

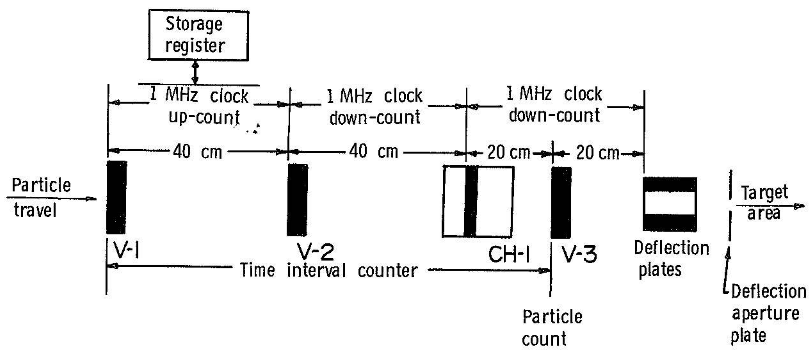


Figure 9. —Data system schematic.

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DATA SWITCH   MODE
14   15
 0    0      A  REAL-TIME
 0    1      B  BY-PASS TAPE
 1    0      C  PRINT OUT OF TAPE
 1    1      D  SYSTEM TEST

SET MODE DS, INTERRUPT
```

INITIALIZATION

```
PROJECT NUMBER            333
TEST NUMBER               003
SPECIMEN NUMBER           023
FILE REFERENCE NUMBER     000001
MAX. PARTICLES ALLOWED    0015000
MAX. ENTRIES ALLOWED      0015000
MINIMUM FLT TIME          0005
MAXIMUM FLT TIME          0250
READY FOR REAL-TIME.
USE DS, AND INTERRUPT TO GO.
```

IDENTIFICATION

```
CHRG   FLT TIME   VOLTMETER
00025   017075   00389
PARTICLE COUNT   0000023

CHRG   FLT TIME   VOLTMETER
00019   016082   00387
PARTICLE COUNT   0000072

CHRG   FLT TIME   VOLTMETER
00012   015444   00390
PARTICLE COUNT   0000117

CHRG   FLT TIME   VOLTMETER
00014   015004   00390
PARTICLE COUNT   0000180

CHRG   FLT TIME   VOLTMETER
00014   015215   00388
PARTICLE COUNT   0000241

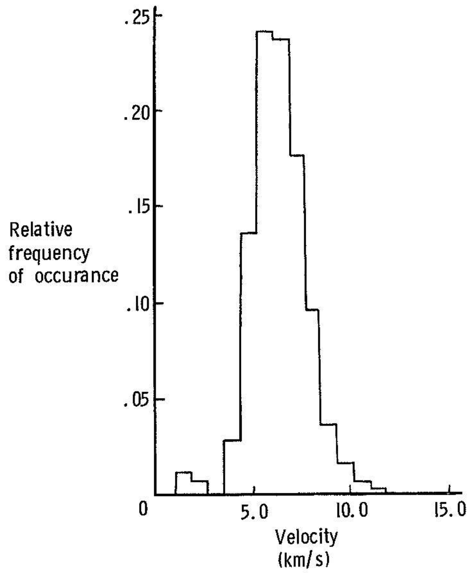
CHRG   FLT TIME   VOLTMETER
00017   015108   00391
PARTICLE COUNT   0000301

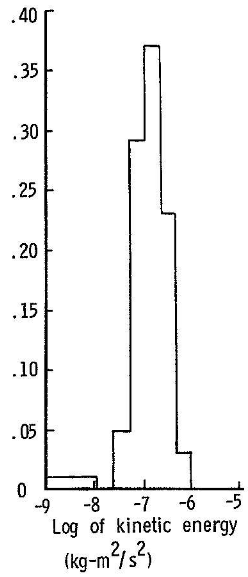
CHRG   FLT TIME   VOLTMETER
00043   017982   00386
PARTICLE COUNT   0000375
```

DATA FROM PRINTER

```
END OF RUN
```

Figure 10. —Data from printer list of experimental run.





(a) Velocity distribution. (b) Kinetic energy distribution.

Figure 11. —Typical results from Data Acquisition System.